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— Thesis —

On the Relations of the Chemical Composition to the Physical Properties of Steel.

Written by

J. Sonderecker

For a Master's Degree in the Course of Civil Engineering

Ills. Industrial Univ.

— 1883 —

Thesis.

On the relation between the Chemical composition and physical properties of steel, including a discussion of the treatment made by the U.S. Board for testing iron and steel.

The subject of the relation between the Chemical composition and physical properties of steel is one which is receiving great attention with Engineers and steel manufacturers. The present knowledge upon this subject is very moderate, owing no doubt largely to the great effect which the process of manufacture has upon the physical properties of the metal. But with an increasing knowledge among manufacturers of the best methods of treating the metal, steel having a given Chemical composition, will possess more uniform physical properties, and a knowledge of the Chemical composition will increase in value as the properties of each ingredient will be more definitely known. Indeed is not the great importance given by engineers to physical tests as compared with Chemical tests due in some degree to the great variations in the quality of the metal caused by the different methods of treatment by the manufacturer, and a lack of knowledge of the metal

of treatment become more uniform it seems probable that chemical tests will increase in importance.

It may be said that chemical tests are useful only to the manufacturer. This does not appear to me to be true. Chemical tests in connection with physical tests are necessary for a complete understanding of the character of the metal. Two bars of steel may have the same strength, elastic limit, ductility &c. and yet different value for many purposes. What physical test will determine the metal best fitted for steel rails? The only certain test at present seems to be the test of actual use. But this would be a very tedious method of making the test. Would not a thorough knowledge of the chemical composition greatly enlighten us in this respect? [illegible] some so and such tests have been undertaken.

Again, how do we know that two steels having different chemical composition but the same physical properties will equally withstand the repeated shocks and vibrations to which Rail Road Bridges are subject. May not a difference in Chemical Composition make a difference in their power to withstand such shocks. This seems at least possible. It would be im-

practicable to subject a bridge steel to the repeated shocks and vibrations to which it is subject in practice. We must rely on less expensive tests, surely a physical and chemical test will define their applicability for a special purpose better than physical tests alone.

Again, an engineer may for some special purpose desire a steel having properties different from any steel in the market, for example the instance of the chrome steel used in the St. Louis Bridge. A knowledge of the properties of the chemical ingredients of steel in such a case would be of value to the engineer enabling him to indicate to the manufacturer the chemical composition which would probably produce steel having the required properties.

These are some of the reasons why it seems to me desirable that the engineer possess a knowledge of the effect of the chemical ingredients of steel as well as a knowledge of their physical properties

Explanation. I do not make a record here of the experiments made in connection with this investigation because they can be readily obtained from the reports of the U.S. Board for testing iron & steel. The experiments in the investigation I arranged the separate results in each physical test in one

three experiments corresponding to a given chemical analysis. If the physical tests in the three experiments were uniform, I gave greater importance to such than I did to those, which I considered varying among themselves. The numbers refer to the corresponding numbers in the record of the experiments.

In the discussion of a series of experiments similar to those, under consideration, the question of what method to follow is an important one. Three general methods have come under my notice 1. Method of least squares, 2. By means of general averages of a number of experiments 3. By inspection or by a comparison of the individual results. The question arises as to which of these methods will probably give the best results.

I Method of least squares. At the commencement of my investigation I employed this method, but reasons independent of the results obtained convinced me that the method was incorrect as I employed it. I employed this method as follows. — Selecting such analyses as differed widely in the percentages of either of the elements present, I formed a series of equations, between the differences in their chemical composition and the corresponding differences in their physical properties. Since the difference in the amount of [illegible]

present in the two cases be represented by $\underline{a}$, of Silicon by $\underline{b}$, of Mg. by $\underline{c}$ &c, and the corresponding differences in breaking strength (for instance) by T, I formed the equation $aC + bSi + cMg = T$, in which C stands for carbon Si, silicon &c. Forming a number of such equations, I reduced them by the method of least squares thus determining the effect of 1st of each of these substances on the breaking strength. Although the results agreed pretty well with those determined by inspection of the same data, still the method was unsatisfactory to me for the reasons which follows

The method of least squares, the equations being put in a form similar to the above would give correct results, first if the effect of Silicon, Carbon &c was constant, i.e. if the effect of 1 % of the element on the physical properties was the same no matter whether it existed in the metal in large or small amounts. Second, if the effect of each element was independent of the presence of other elements. 3rd if the steel was manufactured by the same process and under the same conditions.

I the solution by method of least squares (also by method of general averages) assumes that the effect of an element is constant for varying pro-

portions of the ingredient. This assumption is not true. The addition of .1% of C. to low steel produces a greater change in its physical properties, than the addition of the same amount of C. to high steel, and even produces the opposite effect, i.e. reduces the strength when the percent of C. becomes large (exceeds 1.3% to 1.5%). The results of my investigations sustain me in the conclusion that the effect of an element on the physical properties of steel is not constant

II The method of least squares assumes that each element exerts its influence independent of the presence of other elements. i.e. that Si. will produce the same effect whether Mg. is present in large or in small amounts or not at all. The results of my investigations show also that this assumption is not true.

The 3rd reason (differences in manufacture) of course affects my method of discussion. And besides the large probable error in results of experiments worked by method of least squares indicates its inapplicability.

The above reasons appear to me sufficient to condemn the method of least squares, and the method of general averages in this discussion. These

might possibly be used to demonstrate that the minor constituents would produce little change in the results. These reasons which I at first considered as mere possibilities were confirmed by examination of the data at hand, and afterwards by the testimony of others, so that they appear to me conclusive.

Dr. Raymond, of Brooklyn, in his discussion of the experiments made by Dr. Dudley on the wear of steel rails employed the method of least squares, not so much it appears to deduce correct results as to test Dr. Dudley's results. For as admitted by Dr. Raymond, the method of least squares and the method of general averages are based upon the same assumptions, one of these assumptions being "that the loss of metal (the property under discussion) depends upon the proportions of the various constituents of the rail – that the amount of loss is affected by each constituent in a fixed ratio." ~~and he adds~~, "this assumption I believe is false & the very different results obtained by Dr. Raymond & Dr. Dudley confirm me in this. Dr. Raymond's Equations were of the form $I + cC + pP + sS + mM = L$, in which I is an unknown quantity, depending on the iron and assumed to be constant in all the rails. $c, p, s,$ & m are the experimentally determined quantities of Carbon, Phosphorus,

Silicon and Manganese, & R. is the experimentally determined wear per million tons. C. P. S. & M are unknown coefficients to be determined by solution." "In other words, it is assumed that the difference in wear is proportional to the differences in C., Ph. Si. & Mg. & that the effect of a change in the amount of either is independent of the amount of the rest within the experimental limits of the problem." Of course we would not expect the same results to be obtained by the two methods, because the method of averages is not strictly mathematical but the results should practically agree with each other & we see that they do not. The results of the discussion by the method of least squares as stated by Dr Raymond were as follows "Si, though a hardener increases the wearing capacity, Mg. seems to be neutral behaving like so much iron" &c. the results agreeing with Dr Dudley only as respects the effect of Phos. & Carbon. This difference of conclusions arrived at by methods based upon the same assumptions indicates that the assumptions are incorrect. Prof. Ke[illegible] See (our d. Inst.) says "If the iron and steel does not only contain Carbon & Mg. but also Phos. Si. & sulphur the mg. to a great extent can neutralize, not only the effect of red shortness caused by sulphur but also the tendency of the iron and steel to become [illegible] or

brittle caused by the Phos. and Si. thus brittleness can be as well increased as decreased by the presence of Mg." E. P. Sandberg remarks on the same subject "the amount of Mg. 35% might well be doubled in order to lessen the other 'deadly sins of impurities'." The same idea that the effect of an element is modified by the presence of others is referred to by Wm. Sellers. "It has been found that larger percents of Phos. may be used provided that corresponding changes in the chemical composition be made to accord therewith. My conclusion that Phos. is more deleterious to high than to low steel is confirmed in a general way by the following; "When Carbon is present in quantity with Phos., Si, Mg., & Sulphur, it vitalizes and makes more active all the bad qualities of these elements. My own conclusions arrived at by a careful examination of the data at hand also confirms me in the above reasons as do the quotations just given.

Thus we conclude that the method of least squares & the method of general averages as employed above will probably give incorrect results & should not therefore be employed in this discussion. The only safe way of carrying on such an investigation seems to be by a careful painstaking study of each individual experiment, comparing each with the others, & noting their differences

chemical composition and the corresponding differences in physical properties, & the problem becomes to determine the effect of each in the presence of varying quantities of the others. With this problem in view I proceed to determine the effects of the different elements found in steel from the experiments of the (Watertown) in testing iron & steel. I will give in connection with the results of this investigation some of the comparisons which led me to my conclusions. Then in connection with my own conclusions I will give the conclusions of others as found in various discussions on this subject.

Carbon.

526-528 Very similar in composition with the exception of carbon. Carbon between .6[illegible] % + .830 % increases strength & decreases ductility.

[illegible]-[illegible] Carbon between .50 % & .80 % increases strength & decreases ductility.

1072-1073. Carbon between .980 % & 1.060 % does not alter strength.

1072-1073-1074-1075-1076 show an increase of strength with increased carbon up to [illegible] % although this increased strength was doubtless partly due to increased amount of [illegible].

A careful comparison of a list of experiments pp. [illegible]-802 [illegible] indicates that steel (in this case tool steel) decreases in both breaking strength & ductility.

when Carbon is above 1.% a comparison was made by taking the results of breaking strength per original section & per fractured section in order & comparing with the corresponding %s of Carbon. From this I [illegible] conclude that Carbon increases the breaking strength of steel up to 1% at least. [illegible] — all the experiments show that the effect of Carbon in any amount is to lessen ductility.

Wedding in his work upon Iron & Steel, says with regard to Carbon, "there is also in steel a limit to the % of Carbon beyond which the tensile strength again decreases, so that the characteristics of the material approach more nearly to cast iron. The position of this limit depends likewise upon the presence of other elements." Kent Style gives the % of Carbon corresponding to maximum strength of steel as .8% in puddled steel & 1.2% in Bessemer steel. Marsden gives 1% to 1.5% for greatest strength.

<u>Silicon.</u>

1524-1525-1526-1527. A comparison of these tests indicates that Si up to .35% in steel containing .5% to .7% of Carbon with small amount of Mn, increases strength considerably & does not decrease ductility. The ductility of No. 1526 is no doubt largely due to its higher % of Mn.

1528-1070. Si. from .130% to .230% & Mg from .046% to .071% increases strength greatly, the variation in ductility is slight, the variations in the individual experiments under each number being greater than the difference in ductility of the two numbers

1529-1530-1531-1532. These four steels are very uniform in composition, the varying constituents are tabulated below with elongation and breaking strength.

No. of Expt.	Car.	Si.	elong.	Break. Strength.
1529	.908%	.141%	11.06	20275
1531	.966	.153	10.83	118156
1532	.946	.162	10.50	117993
1530	.927	.187	9.97	123697

These four experiments indicate that as the Si. increases the ductility diminishes regularly. The effect upon the tensile strength is not perceptible. From this comparison we draw the conclusion that Si. above .140% in high steel in connection with very small amounts of Mg. decreases the ductility.

1531-1571. Si. from .153% to .225% and Mg. from .035 to .213% in high steel increases tensile strength considerably but decreases ductility.

No of Expt.	Car.	Si.	Elong.	Break. St.
1533	1.024%	.173%	10.33%	116000
1534	1.079	.096	7.25	110000
1535	1.112	.190	7.31	120000

The percent of Mg. in these three expts. is small. The indications are clear. Si between .1% and .2% in high steel in connection with small amounts of Mg. increases both

strength and ductility considerably.

1053-1056. By reference to each separate experiment under each number we see that the ductility varies more in each set than the means. Thus.

1053	1056	
(1) 16.00%	14.91%	so that no exact result can be arrived at as far as it is concerned
(2) 14.33%	16.92	Both experiments are uniform and the results go to show that
(3) 3.67	16.17	Si. .213% + Mg .073% produce a stronger high steel, than Si .14% and Mg .101% + but Mg it varies in ductility. The greater ductility of 1056 can be accounted for by the higher percent of Mg. So that Si up to .2% is beneficial to high steel not containing over .1% of Mg.

1069-1070. Si. from .170% to .233% in C Carbon steel increases strength but decreases ductility in presence of .190% Mg.

1071-1072 Si from .157% to .225% in high steel containing over .2% Mg. increases strength but decreases ductility. Although it is probable that the Mg. in 1072 aided to increase its ductility

Conclusions. These conclusions only refer to high steel.

I Silicon in high steel as to .2% at least in connection with Mg. not over .1% increases strength & does not effect ductility injuriously. or in these

proportions it is beneficial to high steel. The only comparison which contradicts this conclusion is Nos 1529-1530 &c. but the variations in amounts of Si. present in this case is comparatively small so that the effect may be due to other causes.

II. Si. up to .2 % in high steel in connection with large amounts of Mg. increases the strength but decreases the ductility. (The data seem to indicate that it does not decrease duct)

A rapid examination of Dr Dudley's data indicates that Si. in mild steel for rails increases strength but does not increase ductility. The result may be different however for low steel of different chemical composition.

The U.S. Testing Board says on this element, - that no ingredient of steel is less understood than Silicon "The managers of the Terre Noire works in France who have been notably successful in their steel manufacture believe that Si. up to a few tenths does not decrease the tenacity or ductility of steel, and it is true that good steels are made by various processes with as much as .2 % of Silicon. It is believed by the Terre Noire managers that Silicon in the sense of the bad effects usually attributed to Silicon.

Weyrauch says. "Silicon according to Sandberg of Sweden & others exerts an influence similar to Carbon. Haswell considers it to neutralize to a certain extent the bad effects

of Phosphorus.

Manganese

1523-1067. Mg. up to .40% with .15% silicon without diminishing the strength perceptibly increases the ductility of .40 carbon steel. the greater tensile strength of 1067 being accounted for by its larger % of Si.

1528-1005. Very similar in composition with the exception of [illegible] Mg. and Si. being so near that neither is determinative so far [illegible] the conclusion, [illegible] that the Mg. up to .45% with .30% of Si. in [illegible] carbon steel is to increase ductility. the effect upon tensile strength is not noticeable.

.528-.567. [illegible] composition. the greater amount of Si. in [illegible] would increase its strength so that the experiments show that Mg. from .046% to .82% with .80% Si. in steel containing .4[illegible] [illegible] increase ductility & [illegible] to decrease strength.

.528-.570. Mg. from [illegible]% to .1[illegible]% & Si. from [illegible]% to .233% in steel containing .53% C. increases strength & decreases ductility. The effect [illegible] cannot be determined here.

.521-.507 Mg. from .38% [illegible] with .50% Si. in steel containing [illegible] C.

does not increase

increases ductility largely & ~~decreases~~ breaking strength.

1530-1052. Same conclusion as above. Mg. from .031% to .185% with .10% Si in C. steel increases ductility largely & decreases breaking strength.

1054. The low tensile strength of this steel is not accounted for by its chemical composition. The decided effect of the Mg. can be seen from the table below.

No.	Si.	Car.	Mg.	Elong.	Break. St.
1530	.187	.927	.031	9.87	123697.
1054	.196	.886	.185	17.44	106205.

1530-1072 Although the greater amount of Carbon in 1072 tends to increase the brittleness, the greater amt. of Mn. however increases the ductility. The effect of the Mg. on tensile strength is not so apparent. Mg. .204% with .180% Si. increases the ductility of the metal.

1531-(1058, 1058, 1059) indicates that the Mg. from .035% to .1% with .03% Si. in high steel increases ductility but decreases strength. However, specimens 1058 & 1059 are unsatisfactory, being variable in physical properties & showing a weakness which their chemical composition does not account for.

1531-1071. Mg. from .035% to .213% & Si. from .153% to .225% in steel containing .950 C. increases strength & decreases ductility.

1531-1072. Mg. from .305% to .245% with .50% Si. in .90% C. steel increases strength slightly but does not increase ductility. Mg. in this case seems to change the character of the steel very little

1533-1072. In 1% C. steel Mg. from .30% to .24% with .50% Si. increases strength somewhat but does not alter ductility

1535-1070 Mg. in 1.1% C. steel up to .269/.282% increases strength and also ductility in presence of .19% Si.

1535-1075. Mg. in 1.1% C. steel with .2% Si. up to .22% increases strength and ductility.

No.	Si.	C.	Mn.	Elong.	Break. St.
1536	.14	.956	.32	6.36	119514
1075	.204	.142	.282	11.15	121403

These two experiments show that large amounts of Si. & Mg. are valuable ingredients in high steel increasing both strength & ductility largely. The effect of the Mg. here is clearly to increase the ductility of the metal.

No	Si.	C.	Mg	Elong.	Break. St.
1053	.213	.973	.073	14.67	103000
1054	.196	.886	.185	17.44	106000

Mg. in this case increases strength & ductility of steel. This expt. when compared with others shows that Mg. in small amounts produces a greater & more pronounced [illegible] in the properties of steel than it does in larger amounts.

1053-(1071 to 1072) Mg. from .073% to .200% and Si. from [illegible]% Si. [illegible] in connection with .2% Si. increases strength and no ductility, [illegible] decreases ductility.

1053-1072. Mg. from [illegible]% to .200% in [illegible]% Si. [illegible] increases strength but decreases ductility.

1071-1072. The Si. in this experiment appears to affect the steel more than the Mg.

Mg.

Out of a set of 19 pairs of experiments, which were drawn up with a view to the effect of Mg. on steel, 3 indicated an increase in ductility due to an increase in the amount of Mg. present & the remaining 16 indicated the opposite. but each of these 6 Expts included Expt. No. 1071 & 1072 which have a small ductility so that we conclude from the examination of this table as well as from the other comparisons that in general. I. in steel containing from [illegible]% to .12% carbon, Mg. [illegible] .25% in connection with Si. from [illegible]% to .220% increases the ductility of the metal. II. With regard to the effect of Mg. upon strength, the effect of Si. upon strength is so great that it is difficult to determine what part of the strength is due to the Mg. present. Of the 19 comparisons 13 show an increase in strength & in several cases where the [illegible] Si. is diminished. [illegible]

a decreased strength, [illegible] smaller amount of Si. [illegible], for it, so that we may safely conclude that [illegible] with Si up to 2% does not diminish its tensile strength. [illegible] that Mg. up to 2% [illegible] in connection with [illegible], is beneficial to high steel. In addition to these general conclusions it seems probable, (1) that the higher the percent of carbon in the steel the more Mg. it will take without detriment to its physical properties. (2) In high steel with considerable (.5%–.2%) of Si present the addition of Mg. [illegible] at first increases the ductility, [illegible], [illegible] when a further addition of Mg. decreases the ductility. These two conclusions are merely suggested from the expts: not proved.

The percent of [illegible] was so [illegible] from these expts. determine how the presence of varying [illegible] of Si affects the action of the Mg.

An examination of [illegible] shows that in the mild steel containing from .2% to .5%[?] of carbon [illegible] in the manufacture of [illegible] Mg. increases the ductility of [illegible] up to 7%. These conclusions [illegible]

respect to Mg are only reliable within the limits of the experiments which in high steel between 1 – .25%, & in the mild steel [illegible]

"The [illegible] Board on testing steel says Mg. seems to toughen steel & to make it cast sound. Its hardening effect up to .2% or .3% is slight."

Dr Dudley recommends for steel rails the following composition.– Phos.– not above .1%, Si. not above .04%, C. between .25% & .35%, Mg. between .3% & .4%. These recommendations concerning [illegible] my judgment formed from an examination of his data, agree well with the results of Mg. I think the experiments indicate that Mg. may exist as high as .7% without producing any deleterious effect, on the contrary being beneficial. From the careful examination I have given the data it appears that Mg. from .4% to .7% would produce a better steel than the composition recommended. I refer to the effect upon strength & ductility, not upon wearing power.

P. C. [illegible] in [illegible] says with regard to Mg. "The rail makers both in this country & England are now making steel containing more Mg. than formerly. These rails are going out of the mills

apparently better and sounder than those formerly made". This is confirmed by two tested specimens presented by Mr Hunt - said to be good rails. They had the following composition.

C.	Ph.	Si.	Mn.
I .410	.050	.086	.942
II .350	.057	.082	.820

This will be seen by comparison [illegible] the conclusion that a higher percent of Mn. should be allowed.

Mr. Pourcel of Paris gives the following composition for steel rails which he says have stood the test of actual use, on French railways better than those containing a smaller percent of Mn.

Carbon .50% to .45%, Mn. .80% to 1.10%, Phos. .08% to .1%, Sulphur .05% Silicon .02%. He further remarks on the effect of Mn. in steel that, "Mn. without sensibly diminishing the elongation of steel, increases its tenacity & rigidity as well as its power of resisting shocks, it gives to steel the admirable quality of hardness without brittleness". & remarks in conclusion that "I am of opinion that elements like Phos., Si., Sulphur, must be reduced to a minimum, especially Phos., and Sulphur, but I do not place Mn. in the category of impurities

that are injurious either to the working or use of the ~~steel~~ rail, I should give preference to a metal containing Mg. with the amount of [illegible]. +

A comparison of these four conclusions with reference to Mg. is instructive.

Authority	C	Ph.	Si.	Mg.
Dr. Dudley (from Dr. D's Exp'ts)	.25-.35	.1	.04	.3-.4
Sandr[illegible]ch	.25-.35	.1	.04	.4-.7
R. W. Hunt	.4	.05	.08	.9
M. Pourcel	5 - .60	.08-.1	.12	.9-1.1

From these results we see that the greatest difference lies in the amount of Mg. to use. It may be remarked with regard to the 1st two, tho' the data examined did not contain analyses giving as high percent of Mg. as the last two. The general conclusion however remains that Mg in high amount is beneficial to mild steel, such as that used for rails.

But while we have this strong evidence in support of my conclusions, there are others who claim that Mg. is injurious to steel. The following is from Jour. Frank. Inst. Aug. '81. "Pure iron and pure carbon make the best steel of all degrees of carbonization for all purposes, Si, Phos. & Mg. in random quantities make the metal brittle and are injurious in any amount." This is a pretty broad statement considering that no steel has been made, & any

+ Lang, one of our best authorities says, "Mg. is a valuable ingredient in steel."

knowledge containing only more Carbon.

Weyrauch in his work on Phosphor steels says that they exert a prejudicial influence. This apparent conflict in authorities is no doubt largely due to the difference in the Chemical composition &c of the steel from which the conclusions were drawn. To obviate any such misunderstanding it is desirable that the chemical composition of the steel selected, be given in connection with the conclusions. For it is evident that they may be beneficial under certain conditions & detrimental under other conditions.

<u>Sulphur</u>, <u>Phosphorus</u>, <u>Copper</u>, <u>Cobalt</u>, & <u>Nickel</u>.

These are considered together because in many cases it is difficult to separate their effects.

1081-1082. Phos. is apparently more deleterious to high than to low steel. No. 1081 with .116 C. is not made brittle by .045 Ph. while 1082, .675 C. is very brittle with .065 Ph. [illegible] (see p. 24)

1081-1084. This sustains the conclusion of Haswell given under Si. that Si. neutralizes to a certain extent the bad effect of Phos.

1081-1086. Large amount of Phos. in low steel increases strength & decreases ductility.

No.	Sul.	Phos.	Si	Graph.	Carbon	Mng.	Copper	[illegible]	[illegible]	Elong (per cent)	Elastic limit (per sq in)
1081	.029	.045	[illegible]	[illegible]	[illegible]	[illegible]	.002	—	—	33.39	51833
1082	[illegible]	[illegible]	.128	[illegible]	.075	[illegible]	.022	—	—	[illegible]	[illegible]
1084	.007	[illegible]	.219	[illegible]	[illegible]	.053	[illegible]	.075	.055	27.17	54333
1085	[illegible]	.062	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.065	[illegible]	[illegible]
1086	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.125	[illegible]	[illegible]	[illegible]
1087	.041	.125	.128	.007	[illegible]	[illegible]	.252	[illegible]	[illegible]	6.75	88007
1088	.043	[illegible]	[illegible]	.012	[illegible]	[illegible]	[illegible]	.052	.120	1.76	101045
1089	.011	[illegible]	[illegible]		.042	.051	.028	.025	.044	27.50	48048
1090	.048	.315	.214	.003	.012	.081	.042	.022	.185	22.11	51500
1092	.066	[illegible]	.016	.012	[illegible]	.525	.306	.054	.178	5.65	79315
1093	.058	.128	.013	.011	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	15.20	78500
1094	.056	.113	007	004	135	.165	.364	.076	.107	18.06	68667
1096	.038	092	.170	.012	.375	.685	.210	050	.115	13.72	111203

1081–1093 Large amount of Phos. Sulphur, Copper, [illegible] & [illegible]. makes a very brittle metal of this mild steel.

1081-1094. We here see the combined effect of Sulphur, Phos. Copper. Co & Ni. on mild steel making it so brittle as to be useless.

1082-1085. These confirm the remark made above that Phos. & Sulphur have a more deleterious effect on high than on low steels. No 1085 is a good steel notwithstanding the amount of Phos. present. Its good qualities being apparently due to the large amounts of Mg. and Si. present.

1082-1088 Indicate that large amounts of Copper, Co. & Ni. decrease [illegible] & ductility of steel, It is difficult to determine the effect of each, but we can certainly conclude that Copper is not beneficial to steel.

1084-1089. The larger amount of Phos. & Si. in 1084 have given to it greater strength, It would appear, the ductility being the same that Si. neutralizes the bad effects of Phos.

1084-1090. Shows plainly that Sulphur & Phos. decrease ductility & also strength.

1085-1084 This comparison shows generally the bad effect of Sulphur, Phos. & Copper on steel.

1085-1092 Shows Sulphur & Copper to be detrimental.

1086-1087 This comparison shows the effect of large amounts of Copper. Co. & Ni.

to make steel brittle, an exact comparison cannot be made because of the difference in the amount of Carbon present.

1086-1093. Sulphur & Copper increase brittleness.

1086-1094. Shows satisfactorily the effect of Copper, Co. & Ni. to make steel brittle.

1087, 1092, 1093, 1095. Possess similar properties due to their similar chem. composition. These steels were Sulphur, Phos. Copper, Co. & Ni. absent, would be of excellent quality. These substances make them worthless.

1087-1095. Shows the effect of Si and Mn. Traces of Mn. also to increase the strength of the steel & at the same time neutralize the bad effects of Phos.

1090-1091. Affords a fair comparison for Sulphur & Phos. & indicates that Sulphur & Phos decrease ductility.

Conclusions. Sulphur. As a result of this examination we see that Sulphur increases the brittleness of steel. Weyrauch says "Sulphur is next to Phos. the most injurious ingredient in Steel. It acts similarly to Phos. except that it causes the material to work with difficulty white hot" This inclines some to be of more importance to the same author than to the chemist because he must get rid of the sulphur in order in the steel to work well. It

gives to steel the property called "red shortness"

Phosphorus

This element is also injurious to steel. It increases the brittleness very much & the strength somewhat. It appears to be more harmful to high steels than to low steel. The presence of Si. seems to counteract its dangerous properties. In summation of Dr. D.'s data shows that Phos. may exist in mild steel up to .1% without making it very brittle & unfit for use. Weyrauch states that "Phos. increases the elastic limit & tensile strength of steel but diminishes its resistance to impact. The steel becomes coarse grained brittle & crystalline. Hence steel containing above .2% to .25% of Phos. is unfit for use in technical purposes."

Copper. This substance also seems to be injurious to steel increasing the brittleness greatly without any corresponding increase in strength.

Cobalt & Nickel. These substances being associated with large amounts of Copper & Phos. in the steels examined, it is difficult to determine their separate effect. All that I can say is that I have failed to detect any injurious qualities in them.

Chromium.

177-178-179. It is difficult to tell from these experiments what the effect of Chromium is, 177 being a poor steel, 178 a very good steel Chrom. high in both

The numbers in each of the columns in the table given below indicate the position (in order of merit) which each of the steels containing chromium reaches in a total of 17 tests, given in the Robert [illegible] [illegible] Vol II pp 590-592.

It will be seen that as a rule these steels stand high in the list in 9 cases out of the 12 given. The breaking strength for fractured section results in a higher place than the breaking strength for original section, indicating that the ductility is above the average of these steels.

Break-Lot Orig. 2½" x	Fract. 1¾"	Break-Lot Orig. 2" x	Fract. 1¼"	Break-Lot Orig. Round	Fract. 1"	Break-Lot Orig. Octagonal	Fract. ¾"	No	Carbon	Chrom.	Tensile Strength Orig. Sect.	Fract. Sect.
								a	1.199	900	116000	161441
(d) 5	4	(b) 9	2	9	1	(f) 7	5	b	.825	.640	97000	153000
7	1	1	4	(e) 6	4	9	1	c	.877	.449	111000	[illegible]
(a) 1	2	2	6	(c) 5	3	5	3	d	1.009	.433	109000	138000
								e	.860	.379	108000	144000
								f	.935	.220	114000	142000

Average position for Orig. Sect = 5.5.

" " " Break. " = 3.0.

~~[illegible]~~ The ductility of the steel with manganese [illegible] ranges from 12% to manganese 15% to 18%. The elongation of C. is 15% of original length. This indicates that Mang. in high steel increases the ductility & diminishes breaking strength to a less degree.

Antimony. So far, as the author has seen containing this substance. The effect seems to be to weaken the steel without increasing its ductility.

On the relation between Si & Mg. in Steel.

Mr. Pourcel [illegible] Eng. Mag. says the laws of thermo-chemistry equally confirm the opinion to which I some time ago gave utterance, that when Si. & Mg. exist together in pig iron or steel they are in a state of chemical combination as silicide of Mg. at least if in the ratio of Mn : Si. [illegible] the amount of Mg. increase the hardening properties increases since Mg. increases the [illegible] of dissolving carbon. To show the effect of silicide of Mg. in steel M. Gautier of Paris gives the following experiment, "If we [illegible] the shavings of steel made with silicon only a current of dry chlorine is made to pass, we obtain a network of silicate of iron which preserves the original form of the metal, while in the steel made with silicide of Mg. all of it is dissolved. The latter steel has a greater degree of homogeneity. Each molecule of

metal, not being separated from its neighbor by a layer of oxid of iron or of silicate. This eight exhibits how the steel without bubbles with silicid of mg. presents a resistance to rupture which makes it almost equal to the best kinds of cast steel drawn under the hammer" & in another place. "The steel made with silicid of mg. besides the security which it presents in its homogeneity, presents when it has been hammered or rolled an increased limit of elasticity with a strong breaking strain & a good elongation." Silicid of mg. has the formula Si Mn. or the proportion by wt. of 21 : 27.5. The steel made in the Terre Noire works France, contains large amts of Si. & Mg. but the mg. exist in excess of this ratio. The following is its composition & Phys. properties:-

Carbon .120 %	Limit of Elasticity = 72800 lbs per sq. in.	The metallurgical review Hamsein
Silicon .234	Breaking Strain = 93100 " " " "	gives the following composition
Mg. .527	Elongation measured on 7.87" = 18.7 %	for common C .35 – .40 %
Sulphur .020	Contraction of area = 48.3 %	Si. .25 – .40 % Mg .4 – .6 %
Phos. .104.	Break. Strain per contracted sect. = 180000 lbs	Phos under .06 %.

Several other good steels are mentioned in the same connection having a similar composition to these. It would seem from this that not only do large amounts of si. & Mg.

in mild steel produce a superior metal but that the best effects reach when they exist in a constant ratio, the Mn being the greater in amount.

Conclusion.

This subject of the relation between the Chem. composition and physical properties of steel opens a broad field for investigation. Combined chemical analyses and physical tests seem to be the conditions necessary for any great improvement in the quality of our steel for engineering purposes, — more attention should be given to the chemistry of steel. The old idea that pure iron & carbon will produce the best steel for all purposes seems to me to be contradicted by the results of this investigation, & it seems probable that silicon & manganese will be found upon further trial to be more valuable ingredients in steel than hitherto supposed.

The relations existing between the different substances in steel & the nature of their effects upon each other seems to be complex in the extreme. We find the effect of a substance to vary with its amount and also with the other ingredients present, so that the problem presented is an intricate one.

Not only are we confronted with the problem of finding the effects of different amounts of a substance in the presence of varying amounts of other sub-

stances, but also with that more difficult one of determining the state in which they exist in the metal, whether separate or in Chemical combination with each other. The problem is before us, although much has been done towards its solution, much remains to be done. Advance in engineering construction is hindered by lack of material possessing the required properties more than by anything else, everything done to improve the quality of our structural materials widens the field of work for the Engineering profession.

—The End—

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